VISUAL AND MOTION SIMULATION TECHNIQUES

by

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INTRODUCTION

It is impossible in the time available for this presentation to provide more than superficial coverage of the subjects of vision and motion simulation techniques as these have been applied in space flight research. Fortunately, the excellent presentation by Vogeley on the existing and planned simulators for space research in the NASA program reduces the need for any extensive treatment of the application of techniques which provide for a complete visual simulation. I will therefore discuss problems of visual simulation in more general terms and treat fundamental characteristics of the visual system which are relevant to successful simulation techniques rather than discussing specific applications of these techniques. It may then be useful to consider the way in which sensory information is integrated and processed in our attempt to realize from it a knowledge of the physical world. This will provide an introduction to the discussion of motion and clarify the reasons for including motion cues in simulators.

VISUAL SIMULATION

There are a variety of visual capabilities which will be important in space flight (5). Some of these need not be considered in relation to continuous task simulators, however. Our primary concern is with simulators which provide a basis for testing man's performance in a continuous task situation such as the control of a moving vehicle. We will not discuss the important problems of visual search, detection, and recognition. Visual tasks which are of concern to us are those of the discrimination of size, distance, and relative motion (20, 22, 32).

Visual Size Discrimination

Typically, the discrimination of size of an object is based either on a knowledge of the physical sizes of objects around it in the visual world, or else on a knowledge of its distance from the observer. It is extremely difficult to make accurate judgments of size in the absence of such cues.

Distance Judgments

The judgment of distance is based on a number of cues (20, 22). An important one is that of linear perspective. This refers to the gradual decrease in the visual angle subtended by elements in the visual world as they are located further and further away from the observer. It may relate to the texture of the terrain or, to cite a familar example, the apparent separation of railroad tracks as they recede toward the horizon. This kind of cue is of far greater importance to one who is living on an apparently flat, extended surface than it would be to someone living in relatively empty three-dimensional space without a continuous distribution of objects and terrain from his immediate location out to the location of an object whose distance he desires to judge.

Another important cue is that of interposition. Stated simply, this refers to the fact that an object whose outline or surface is interrupted by another object will be judged further away than the interrupting object. The interposed object is obviously the nearer object.

At surface of the earth, atmospheric haze provides an important cue for the judgment of distance. The reduction by haze in clarity of object detail and the reduction in the range of color seen reflected from an object provides cues as to the object's distance. Another important cue is that of monocular movement parallax. This refers to the fact that when an observer is himself moving he will see relative motion in the visual world between nearby objects and objects more remotely located. The nearby object will appear to be moving in a direction opposite to his own motion. Telephone poles seen from a train window relative to the distant horizon afford a familar example.

Unfortunately, all of these cues require either a distribution of objects in depth from the observer, familarity with the object, or other conditions which are found on the earth's surface. Many situations in space flight may be devoid of all of these cues. Judgment involving other space vehicles may be among the most difficult, but even judgments of surfaces will be difficult when they are normal to the line of sight, and especially when they are unfamiliar. Recent photographs of the surface of the moon show a remarkable continuity in the nature of its appearance from a distance of thousands of miles down to a distance of thousands of feet. Apparently the size of moon craters varies over a continuous range from extremely large to extremely small. This renders it difficult to make judgments of distance or size on the basis of visual angles subtended by details of the surface. A careful examination of the surface presented in Figure 1 is of little help in assessing its distance. As soon as a familiar object is included however, as in Figure 2, the judgment of distance and size is a simple matter.

There is an important cue to distance which does not depend upon object familarity. This is the cue provided by the fact that the two eyes of a binocular observer are located at different points in space and hence see the world from slightly different perspectives (22). Thus an object with some extent in depth may be seen as three dimensional as long as this cue is operating, or two objects at different depths can be correctly discriminated in relation to which is closer and which is further away with no knowledge of their relative size. It has been demonstrated that deviations from the stimulation of precisely corresponding points on the two retinas of less than 30 seconds of arc can be discriminated as representing differences in depth. Rays of light from an object in space at an infinite distance will be parallel on entering the two eyes. One can calculate the distance at which rays of light from an object will deviate by an angle of 30 seconds of arc or more on entering two eyes separated by the normal interpupillary distance of 65 mm. The distance is approximately 500 yards. Thus objects at 500 yards or less should be seen as closer than much more distant objects purely on this basis of binocular stereoscopic vision and independent of their size or shape. The value of such a cue should not be discounted for certain phases of a space mission.

Movement Discrimination

The relative movement of objects in the visual world is discriminated in terms of changing visual angle (10, 11, 12, 21). For objects which are moving in a frontal plane relative to the observer, angular rate is assessed in relation to the changing visual angle between the moving object and some fixed reference point. In the absence of any stable reference point, such a judgment may be extremely difficult. The approach or recession of an object of finite size is inferred from changes in the visual angle subtended by its breadth. A large amount of basic research has been conducted on the minimum thresholds for detection of angular change in the visual world (10, 12). These thresholds will provide a basis for the estimation of boundaries within which visual motion may play an important role in simulation.

SENSORY INTEGRATION

Most individuals would agree that their perception of the visual world is put together on the basis of information derived from the various senses. They would also agree that it is not necessary to make any conscious effort to perform this integration but rather that it occurs quite unconsciously. They might be disturbed at the notion that information derived from various individual sensory channels cannot always be consciously separated and identified in relation to its source, however. There is evidence that the integration of various sensory inputs depends upon experience and requires considerable learning (28). On the other hand, there is also evidence that it may be difficult or impossible to separate information provided by one sensory channel from information provided by another. A recent experiment provides an example of this (29). If a man is seated in a chair and views a vertical line of light directly in front of him, he can recognize its orientation and make corrections when it is deviated from the vertical. If his chair and the vertical line are both tilted away from the vertical he is able to correct the line orientation back close to the true vertical. The basis for his correction must depend upon information which he receives from the deviation of his own body orientation from vertical. One source of such information is the imbalance in tension of the musculature on the sides of the neck which maintains the head in an erect position. If now, an observer is seated erect while wearing a helmet which can be weighted on one side, his visual perception may be distorted by this off-balance load on the neck muscles even though he is perfectly aware that he has not been deviated from an upright position. Differences in tension in the sternocleidomastoid muscles on the two sides were measured electromyographically for various amounts of body tilt. The same differences in tension were then created by off-balance loading, and a truly vertical line was judged to tilt in amounts comparable to the amount of body tilt which corresponded to the differential tension. Thus, in a restricted visual situation where only a single illuminated line could be seen, muscle tension had an important influence on visual perception.

Changes in the resultant acceleration force on a man induced by motion on a centrifuge are perceived via tactual and other cues. In this kind of a situation the orientation of the entire environment seems to change (23). The apparent change in orientation of the environment cannot be eliminated even by the most sophisticated conscious analysis on the part of the observer of the forces at work.

Much more elaborate gyrations of the visual world result from movements or rotations of the head which are not along or about an axis about which the body is being rotated (24). Forces induced by head movement during rotation of the body result in stimulation of the vestibular mechanisms of the inner ear. Vestibular stimulation may have a profound effect on visual perceptions (25).

It is clear that the senses cannot be regarded as independent in their function and even conscious effort may not be sufficient to separate out information provided by one sense modality from that provided by another (18). This situation has posed a serious problem for modern aviation, particularly with respect to vestibular function. The vestibular mechanism is useful and appropriate for a man residing on the earth's surface, but its outputs are quite inappropriate in many of the angular motion situations encountered by aviators (1). This is attested by the tremendous difference in accident rate between IFR and VFR conditions. In order to fly instruments, a pilot must learn to discount all of his senses save vision, and visual information is presented to him in a highly artificial manner. Oftentimes false perceptions which result from vestibular stimulation may override the information obtained from instruments and accidents are the result. It has been estimated that more than 80% of aircraft accidents which are not a direct result of equipment failure are the result of illusions or false perceptions. It is conceivable that these problems may be even more serious in certain aspects of space flight.

VALUE OF MOTION SIMULATION

In the preceding section we have discussed problems which result from false perceptions induced by movement. An extension of this discussion provides a justification for adding motion to a simulator which is not often heard. If the motions of flight may give rise to false perceptions, then in their absence a pilot might be expected to perform better than in the real life situation. Thus if motion is added, a more pessimistic but more realistic assessment of pilot performance may result. Unfortunately, in any laboratory simulation the simulation of motion will necessarily be so limited that its use can never be justified on these grounds. Only in the variable-stability aircraft simulator discussed earlier by Westbrook can a reasonably accurate simulation of motion qualities of a vehicle be achieved. This is a highly specialized type of simulation, however, and far superior to the laboratory simulations with which we are concerned here.

The most frequently heard justification for the addition of motion cues is that they afford an increase in realism. When this justification is applied to situations in which motions are not extreme it must be examined very carefully. There is very little satisfactory evidence to validate the assumption that the addition of motion cues in a laboratory simulator actually increases realism. In an earlier discussion the speaker referred to the importance of subjective opinion in assessing simulations. The subjective opinions of experienced pilots are indeed most important (15), but they alone are not enough. Another speaker referred to a simulation situation which was so realistic that in an emergency, a crew man injured his head in an effort to escape through a dummy hatch. This kind of an anecdote certainly implies some validation of the realism of the situation, but it is hardly a sufficient basis for assessing the real value of the simulator. The value of a simulator must be measured in terms of how well it improves our ability to predict the way a pilot will do his job in the situation which is being simulated.

There are some situations in which the best judgment dictates that motion be added even though its importance is not subject to immediate validation. These situations include all those where motion characteristics are extreme. An excellent example is the X-15 research rocket aircraft (14). The design characteristics of this vehicle were such that fairly extreme conditions of linear acceleration were anticipated during reentry from high altitude missions. In the event of damper failure these accelerations and the conditions of motion were expected to be even more extreme and in a range where the maintainance of control by a pilot was in serious doubt. For this reason, some simulation of linear acceleration profiles was considered imperative prior to actual flight testing of the X-15, even though it was recognized that in certain respects these motion simulations would be inaccurate.

TECHNIQUES OF MOTION SIMULATION

Motion may be characterized in relation to three orthogonal axes of angular motion and three orthogonal components of linear motion. It is possible to duplicate all six degrees of freedom of motion of a maneuvering vehicle precisely only by utilization of the same motion and the same amount of three dimensional space. This is obviously impossible within the confines of a laboratory. Techniques of motion simulation in the laboratory are therefore usually based upon an incomplete simulation in which certain of the six components are neglected (i.e. permitted to assume whatever values are required for a precise simulation of the other components with the available equipment), or an attempt is made to include only those motion characteristics which can be detected by a human pilot.

Angular Components

In conventional flight, the angular components of motion are probably most important. In those instances where they may not be, a justification for considering them rather than linear components can be made on practical grounds. Realistic simulation of linear components of motion with respect to acceleration is possible only with some sort of centrifuge device if the required space is to be limited to even a fairly large laboratory. In most motion simulators therefore, the concern is with angular motions, specifically with angular acceleration.

Detection of angular motion. The most important of the sensory mechanisms for the detection of angular motions is the semicircular canal system of the vestibular apparatus (19). This is illustrated in Figure 3. On each side of the head there are three canals in mutually perpendicular planes, with a lateral canal inclined upward in the front at an angle of approximately 30° from the horizontal, and a superior canal and a posterior canal the planes of which are each at an angle of approximately 45° to a median plane through the head and tilted backward at approximately 30° from the vertical such that they are each perpendicular to the lateral plane. Thus the lateral canals on each side are approximately in the same plane and the superior canal on one side is in a plane parallel to the plane of the posterior canal on the opposite side. Each canal contains a fluid which moves relative to the canal as a result of rotational inertia during angular acceleration. Relative movement of the fluid within the canal causes deflection of a structure called the crista within an enlargement in the canal. This is illustrated in Figure 4. The bending of hair cells of the crista gives rise to sensory stimulation. The compound output of sensory activity from all six semicircular canals is uniquely determined by the orientation and magnitude of angular acceleration.

There is, of course, a threshold for the detection of angular acceleration. This will vary with the method of testing and other circumstances, but will fall somewhere between 0.2°/sec and $2°/sec^2$ (30, 31). The latency of detection of an angular acceleration will also vary with the level of acceleration (16). This is illustrated in Figure 5. From a knowledge of these thresholds, it should be possible to introduce angular acceleration in a simulation only for those circumstances where angular acceleration in real vehicle motion is above threshold. At all other times angular motions in the reverse direction may be introduced at accelerations below threshold in order to return the simulator structure to some neutral position. This procedure is called the "washout" technique. Its application (17) is illustrated for a roll maneuver in Figure 6. In the upper graph, roll angle (ϕ) is illustrated as a function of time. The first and second derivatives of ϕ are illustrated in the succeeding graphs. Solid lines in each graph represent the value for an aircraft. Dotted lines illustrate the way in which the derivatives of ϕ can be approximated even though the actual value of ϕ at the end of the maneuver is the same as the initial value.

By considering the angular terms which describe a typical vehicle maneuver and relating these to the thresholds for angular motion of the human pilot, it should be possible to determine the minimum necessary space in which angular acceleration could be simulated realistically in a laboratory. The procedure would require the use of motion introduced at sub-threshold levels of angular acceleration to return to neutral or median positions whenever maneuvers did not demand the application of supra-threshold accelerations away from the neutral position. If threshold values for the detection of angular accelerations based on laboratory studies are employed, the result of such an analysis will be unduly pessimistic in terms of the predicted space requirements. The thresholds of laboratory investigations are far lower than those which would be appropriate for a complex situation in which a subject is bombarded with many other distracting cues. Nonetheless, an analysis of available data might prove of great utility.

Any large scale effort to apply motion simulations according to these general procedures should include some kind of validation program. There is always the possibility that the addition of artificial motion cues may render the results of simulator studies less valuable for prediction than would have been the case had no motion cues been added.

Linear Components

Linear acceleration components which affect a pilot are illustrated in Figure 7. These are named in terms of the orientation of their line of action with respect to the long axis of the human body (13). Direction is considered to be that in which the man will tend to move against his restraint, rather than the direction of action of the accelerating force. Positive g refers to the component which tends to "pull the pilot down into his seat". This component of linear acceleration interfers with the circulation of blood toward the head. It is therefore of considerable physiological significance. Negative acceleration acts in the opposite direction and aids the flow of blood to the head. Its effects are even more serious than those of positive acceleration because it can cause cerebral hemorrhaging. The effects of transverse fore-and-aft, and transverse lateral accelerations are not as serious if a pilot is given adequate support and restraint.

Some of the maneuvers which induce various forms of acceleration are illustrated in Figure 8.

Centrifuge Simulation

Laboratory simulation of linear acceleration components can only be accomplished with the aid of a centrifuge device. The largest of these which is currently available is the navy centrifuge at the Aviation Medical Acceleration Laboratory at Johnsville, Pennsylvania (17). This is illustrated in Figure 9. In recent months the arm of this device has been replaced and a new and larger gondola mounted in a two gimbal system has been located at its end. The radius is 50 feet and the device is capable of accelerating at an angular rate which produces a centripetal force on objects located within the gondola of greater than 40 g in less than 10 seconds. By rotation of the gondola about its two independent gimbal axes it is possible to vary the orientation of the resultant acceleration force with respect to a subject within the gondola to conform to variations in the orientation of the resultant linear acceleration force in any desired motion pattern. The outer gimbal quadrant gear and the 360° circumferential gear of the gimbal system are illustrated in Figure 10.

The resultant acceleration force in a rectangular coordinate system of three dimensions is calculated in accordance with equation 1.

$$A = (a_x^2 + a_y^2 + a_z^2)^{1/2} \quad . (1)$$

The resultant acceleration force on a man in a centrifuge gondola reflects components due to the earth's gravitational field, the angular velocity of the arm, and any tangential acceleration forces which result from variation in the angular rotation rate. The calculation of this resultant acceleration is illustrated by equation 2.

$$A = (g^2 + \omega^4 L^2 + \dot{\omega}^2 L^2)^{1/2} \qquad (2)$$

If appropriate gimbal motions can be calculated in order to obtain a proper time history of orientation of the resultant force, then any linear acceleration time history within the capability of the centrifuge can be described in terms of equation 2 and the appropriate values of outer and inner gimbal position as a function of time.

Catapult launching. A very simple simulation (7) is illustrated in Figure 11. The outer gimbal was so positioned that the gondola and the pilot in his seat faced in the direction of rotation. At the instant the arm was started, the largest acceleration component produced by the arm was the tangential component forcing him back into his seat. As angular velocity increased the centripetal force increased and the gondola was rotated toward the center of rotation of the arm. Rotation was continued in such a way that the resultant acceleration from the tangential component and the centripetal component was always oriented from chest to back through the pilot. In this fashion it was possible to impose a linear acceleration component on a pilot similar in its orientation and magnitude to that encountered in a catapult launching. Unfortunately, the temporal response characteristics of the centrifuge system are far too slow to achieve the abrupt onset of acceleration which is characteristic of a catapult launching. Nevertheless, the technique is illustrative.

The X-15. The aforementioned simulation of the X-15 research aircraft was accomplished on the navy centrifuge. A cockpit simulation was installed within the gondola. A photograph of the instrument panel used in this simulation is illustrated in Figure 12. All of the important flight instruments were operative and their indications changed in a manner appropriate to the mission under simulation (2, 8). Some justification of the importance of this simulation may be obtained by an examination of the acceleration time history of positive g predicted for a situation during a reentry with air brakes closed and failure of the pitch damper. This is illustrated in Figure 13 by the dotted line. There is a relatively high frequency oscillation of acceleration between 4 and 8 1/2 g's. This is a range in which unconsciousness is induced in many subjects. It was therefore considered extremely important to determine whether a representative sample of test pilots could continue to perform any effective control of the vehicle during exposure to accelerations of this kind. The best that could be achieved on the centrifuge is illustrated by the solid line in Figure 13. The reduced amplitude of oscillation is a result of the frequency characteristics of the centrifuge system itself. In spite of the fact that these accelerations are not as severe as those predicted from the vehicle design, the possibility of demonstrating that a pilot could withstand them and continue to control his vehicle was of some importance. The accomplishment of this demonstration added considerably to the confidence of all concerned with the X-15 program.

Satellite launching. Another situation in which extreme acceleration forces were a matter of concern was that of the launching of a multi-stage orbital vehicle (3). An acceleration time history which is representative for such a vehicle is illustrated in Figure 14 by solid lines. The centrifuge simulation is shown by the dotted line. It is clear that the centrifuge provides a reasonable approximation of the linear acceleration time history. It is limited for two important reasons. In the first place, it is not possible with a centrifuge rotating in a horizontal plane to introduce any motion component which will offset the earth's gravitational field. Thus all resultant accelerations will include the component of gravity and it will not be possible to reduce the resultant acceleration force below 1 g at any time. This limitation is illustrated after the third stage in the Figure 14. Another important limitation is the fact that to change the acceleration component due to angular rotation of the arm requires the introduction of a tangential component of acceleration. If any attempt is made to change angular rate abruptly the magnitude of the tangential term will be prohibitively great. Changes must therefore be made gradually. This is illustrated in Figure 14 by the reduction of acceleration at a finite rate at the end of each stage.

Results of centrifuge studies. Several specific findings of importance were derived from simulator studies on the navy centrifuge. In the case of the X-15, it was found that the scanning pattern required for adequate control of the vehicle was difficult with the instrument panel layout first used (8). This difficulty might not have been considered significant had the pilot not had to contend with the high linear acceleration forces.

In the case of the orbital vehicle, a side arm controller was found by four test pilots to be loaded inappropriately during the simulated exit accelerations (3). The loading of this controller had been selected as optimum by these same test pilots in a static simulator. Both the loading and the balance were improved following centrifuge simulator studies.

Another important finding from this experiment was the fact that pilots can and must learn to cope with acceleration forces (3). This is illustrated in Figure 15. Pilots' scores on a tracking task are illustrated in terms of integrated error in pitch control as a function of trial blocks. It is evident that performance improves markedly from the first through the last trial block. Three of the pilots had had extensive training in the tracking task in a static simulator prior to exposure to acceleration. Interspersed with determinations of tracking performance under acceleration, trials with the centrifuge stationary were given in order to provide a reference level of performance. The three pilots who had had prior static training showed a high level of proficiency and little or no further improvement during the course of these stationary control tests. On the other hand, the pilot who had received no prior static training did just as poorly during the stationary tests as under acceleration, but his performance under acceleration was comparable to that of the other three pilots. In this situation, training in a tracking task under stationary conditions apparently resulted in no improvement of the same tracking task under acceleration. The task was like a completely different one when acceleration was added.

Closed-loop operation. In the situations that have been considered thus far, the motion of the centrifuge was preprogrammed and the control manipulations of the subject had no direct effect on the acceleration to which he was exposed. In actual practice one can expect an interaction between acceleration effects and the pilot's control manipulations. Each will influence the other. These situations have been studied on the navy centrifuge with a simulation technique which is illustrated in Figure 16. In this case, vehicle dynamics are simulated on an analog computer (17, 26). A pilot's control manipulations are fed to the analog computer, which then calculates vehicle motion. This is converted to appropriate terms for the control of the centrifuge. These are fed back to the centrifuge drive system and result in motions which produce a linear acceleration time history on the pilot appropriate for his control manipulations. At the same time, the instrument display presents information appropriate to the maneuvers being performed. This kind of a simulation is limited by the frequency response characteristics of the arm itself and of the outer and inner gimbal systems. The main arm provides the primary limitation and outer and inner gimbal responses must therefore be delayed in order to maintain synchrony among all three systems. This delay can be compensated by taking advantage of delay which is characteristic of the aircraft system and including centrifuge delays within this delay time in the computer system.

The closed loop simulation techniques has been employed in a variety of programs (4). Subjective impressions of its value vary considerably with the nature of the program. For the simulation of conventional aircraft maneuvers, pilots are uniformly agreed that the simulation is poor. It must be remembered that only the linear acceleration components can be accurately simulated with this device. Only highly approximate simulations of angular effects are possible. In some cases, in order to maintain the proper orientation of a resultant linear acceleration force it is necessary to introduce an angular rotation in the opposite sense from that which would occur during an aircraft maneuver. This is disconcerting to a pilot who is highly dependent in his control manipulations on the sensory feedback from motion cues, whether he is willing to admit it or not.

Fortunately, the effect of angular accelerations on a pilot appears to diminish as the magnitude of linear acceleration is increased. Therefore, in situations such as the X-15 where high amplitude linear accelerations were encountered, and in orbital vehicles where high linear accelerations and relatively low angular accelerations are encountered, the centrifuge simulation is extremely valuable.

A tracking experiment. The effects of centrifuge motions on the performance of a tracking task (6) were studied with a cockpit simulation like that illustrated in Figure 17. A tracking task command signal was presented on an oscilloscope mounted over the panel. It was the pilot's task to maneuver his aircraft so that a target spot was maintained centered on the scope. Results of this experiment are illustrated in Figure 18 in terms of cumulative error scores for vertical tracking, horizontal tracking, and flight coordination. The solid black bars illustrate performance with the centrifuge stationary. The cross-hatched bars illustrate performance with the centrifuge in motion. It is clear that performance in the vertical tracking task is poorer with the centrifuge in motion than under control conditions. On the other hand flight coordination is far superior with the centrifuge in motion than under control conditions. The reason for this is clear: if the centrifuge is in motion the pilot is given constant reminders of imperfect flight coordination in the form of jostling which may reach unpleasant proportions. It is therefore more important to him to control this dimension than it is in a stationary situation. The degradation of his performance with the centrifuge in motion can probably be attributed to the distraction afforded by the requirement that he pay more attention to flight coordination.

A validation experiment. I have expressed concern for the requirement that simulators be subjected to validation. An effort has been made to do this with the Johnsville centrifuge relative to its possible use for the simulation of conventional aircraft (9). The TV2 cockpit interior illustrated at the bottom in Figure 19 was duplicated within the centrifuge gondola as illustrated at the top of the figure. A tracking task signal was recorded on magnetic tape in terms of both pitch and roll commands as illustrated in the top two traces of Figure 20. Errors in following these commands were recorded and are illustrated in Figure 20 in the third and fourth traces from the top. The control surface deflection angles for both ailerons and elevators are illustrated in the bottom two traces of the figure.

Six subjects were employed in the experiment, and all six flew the aircraft, a static simulation of the aircraft and two centrifuge simulations. The two centrifuge simulations consisted of one which represented the linear acceleration components as accurately as possible and another which included angular accelerations in the correct sense at the initiation of each maneuver with some loss on the fidelity of linear components. This was accomplished by means of a high-pass filter in the gimbal system.

Results in terms of integrated error for the control of the roll dimension are illustrated in Figure 21. There is a striking similarity in the profile of performance of the three test pilots in the four different experimental conditions. The performance of the navy pilot is similar but somewhat different, and the performance of the two non-pilots is even more different. One of the non-pilots who had had extensive centrifuge experience performed best on the centrifuge but proved poorest in performance of the task in the aircraft. The pilots all had their poorest performance on the centrifuge and best in the aircraft. These results suggest that there may be negative transfer of training between a centrifuge and an aircraft. Training in one may tend to degrade performance in the other. The reasons for this, if it is true, may be based precisely on those angular motions which are sensed by a pilot in an aircraft and which influence his control manipulations even though he may be unaware of the fact. For a subject trained on the centrifuge the angular terms are quite different, and if they feel natural to him it is to be expected that an aircraft will seem unnatural and strange.

This discussion has been based on integrated error scores. Another kind of data analysis which leads to somewhat different interpretations of the same experiment (33) is illustrated in Figures 22 and 23. In Figure 22, an autocorrelation of the pilot's performance in control of roll has been calculated for each of the four conditions of the experiment. The form of the autocorrelation function depends on the frequency components of the control motions. It is clear that the form of the autocorrelation function is more nearly similar for the centrifuge simulations and the aircraft than it is for the static simulation and the aircraft. It is most like the aircraft in the centrifuge simulation which included angular acceleration terms. The form of these autocorrelation functions shows that the subject employed a higher frequency response function for his control manipulations in the static situation than he did on the centrifuge. His frequency response was lower when angular terms were included than for the linear acceleration simulation, and still lower in the aircraft. In terms of results presented in Figure 22, performance in the aircraft could best be predicted from the centrifuge simulation with angular motion terms added. An elaboration of these results which supports the same conclusion is presented in Figure 23. Here, power spectral density, calculated from the autocorrelation function, is presented as a function of frequency. Power is increasingly restricted to the lower frequency domain with a transition from static simulation to centrifuge I (pure linear), centrifuge II (some angular), and finally the aircraft. Pilots become less likely to employ abrupt control manipulations the higher the penalty for a mishap.

Psychological Stress

The psychological importance of centrifuge simulations of the kind described for the X-15 and for orbital vehicles has been justified by the comments of pilots of the X-15 and the Mercury astronauts. All of these individuals felt that exposure to accelerations in flight was far less disturbing than it would have been had no prior experience under laboratory conditions been available. The centrifuge helps test pilots of these experimental vehicles to get over at least some of the psychological hurdles which otherwise would have to be taken in the first test flight. Evidence that a ride on the centrifuge may itself induce some anxiety (7) is illustrated in Figure 24. Heart rate in these graphs is presented as a function of acceleration level. It is clear that in the case of the dotted line there is an increase in heart rate with acceleration.

The important consideration in this case is the fact that these heart rates were measured prior to exposure and immediately after the subjects learned what acceleration level they were about to be subjected to. If one can assume that an elevation of heart rate is an index of anxiety, then it is clear that the anticipation of acceleration exposure can induce anxiety. This may be of real value. The inability to induce the fears which will attend an actual test in a laboratory simulation of the test represents a serious weakness in most simulator programs.

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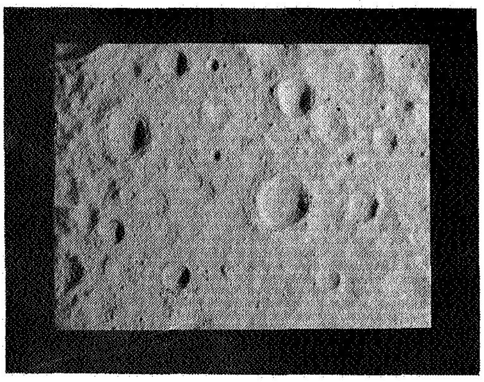

Figure 1: An unfamiliar surface which illustrates the difficulty of size and distance judgments.

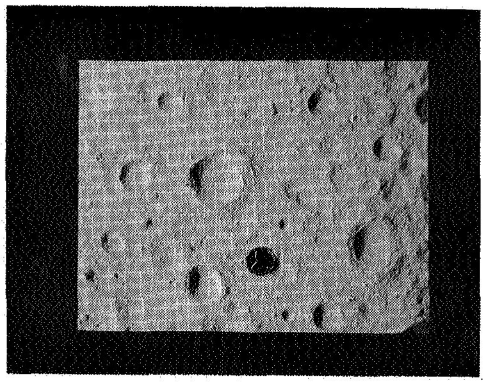

Figure 2: Judgment is influenced by the presence of a familiar object.

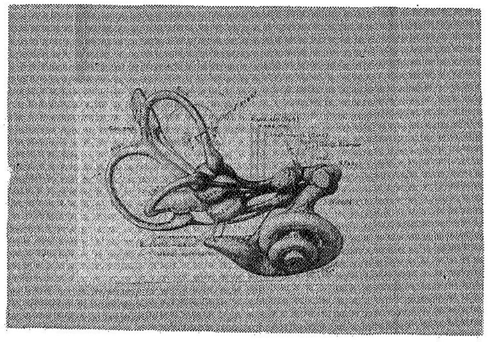

Figure 3: The human labyrinth: semicircular canals, utricle and saccule, cochlea (Hardy, 1935).

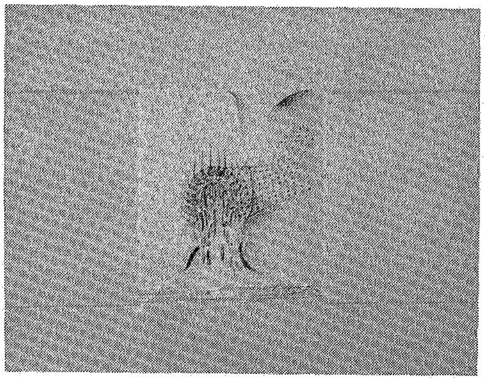

Figure 4: The crista of the semicircular canal (Wersäll, 1956).

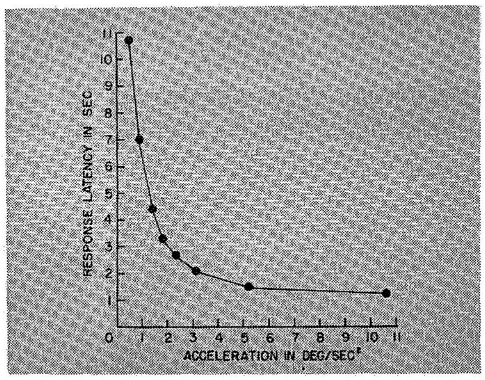

Figure 5: Latency of response to rotation as a function of angular acceleration (Crampton, 1958).

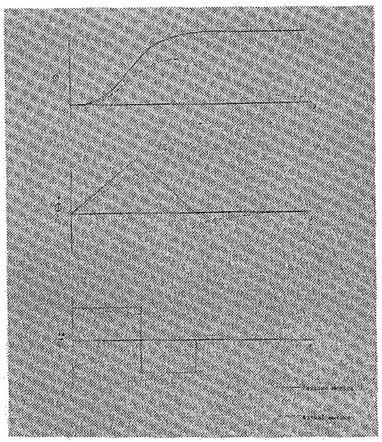

Figure 6: Roll angle and roll angle derivatives which demonstrate the "washout" technique. Solid lines represent values for an aircraft maneuver; dashed lines represent values employed in a simulator (Fischer and Nicholson, 1959).

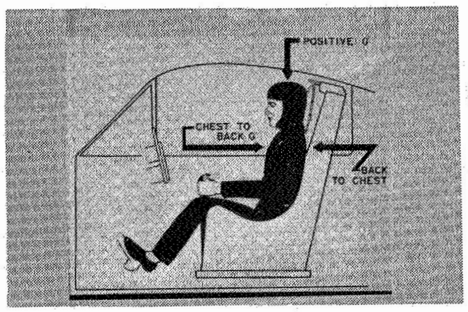

Figure 7: Components of linear acceleration which act on a pilot in the median plane.

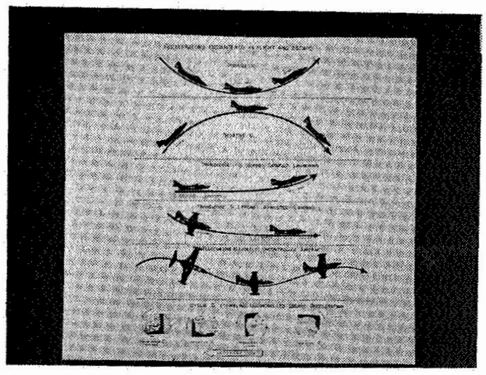

Figure 8: Aircraft maneuvers and the types of acceleration to which they subject the pilot.

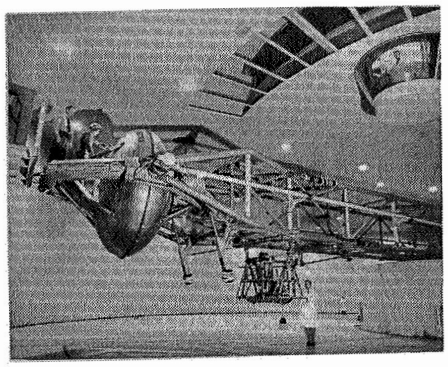

Figure 9: The navy centrifuge at Johnsville, Pennsylvania.

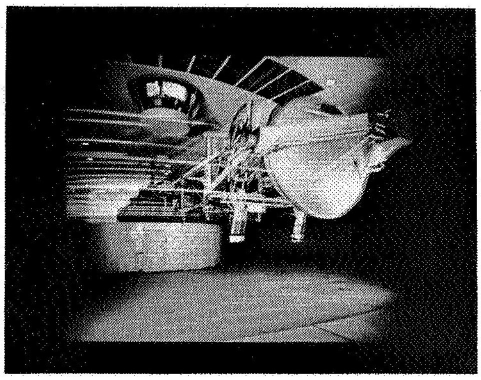

Figure 10: Illustration of the gearing of the gondola gimbal drives.

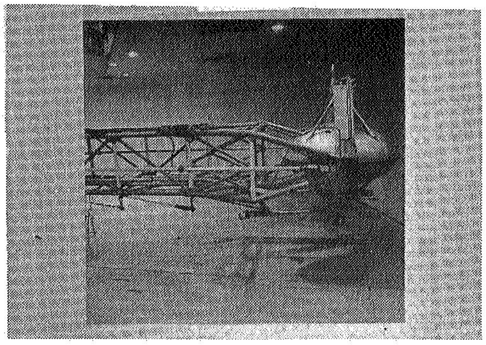

Figure 11: Centrifuge gondola positioning for simulation of a catapult launching.

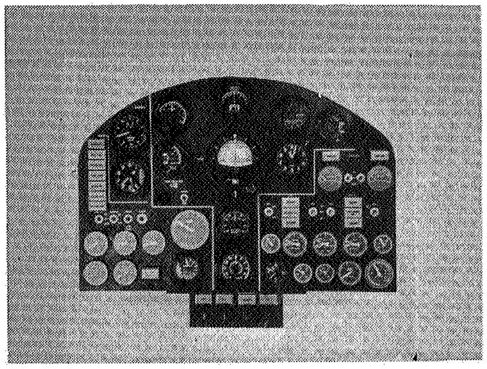

Figure 12: The instrument panel employed on an X-15 simulation.

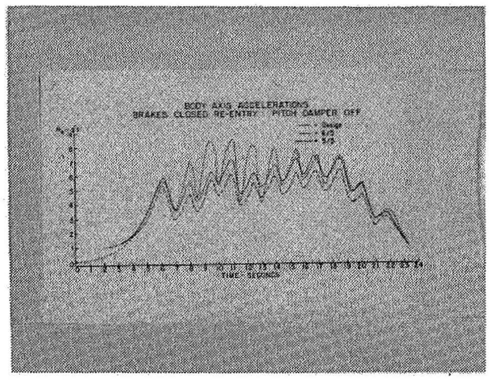

Figure 13: A computed positive acceleration time history for X-15 reentry (dotted line) and two approximations of this time history by the navy centrifuge.

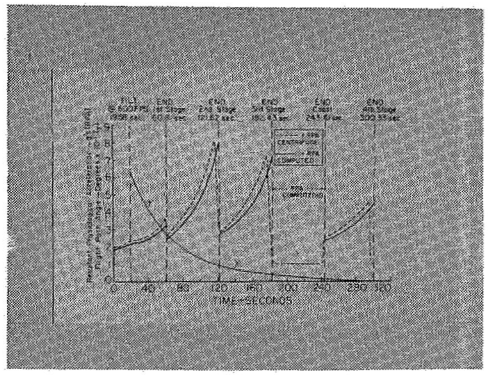

Figure 14:

An acceleration time history for launch of a 4-stage orbital vehicle. Solid lines represent actual value; dashed lines represent centrifuge simulation. Flight path angle is also shown.

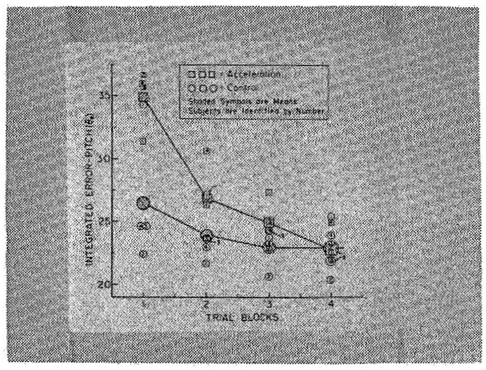

Figure 15: Integrated error scores on successive blocks of trials for performance of a tracking task during simulation of the launching of a 4-stage orbital vehicle. Squares represent data obtained during exposure to acceleration; circles represent data obtained with the centrifuge stationary.

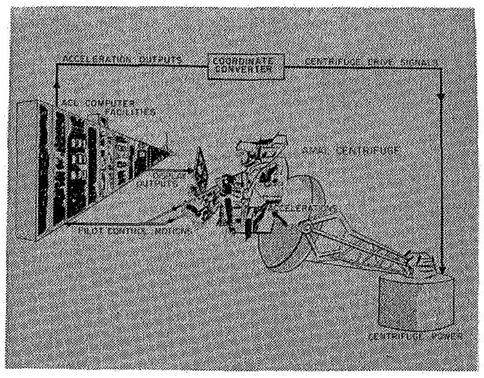

Figure 16: Schematic illustration of closed-loop computer control of the navy centrifuge.

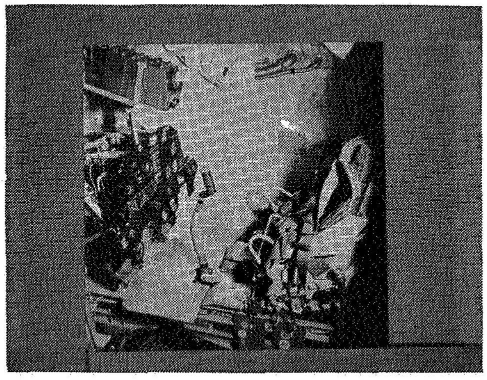

Figure 17: A cockpit simulation in the centrifuge gondola.

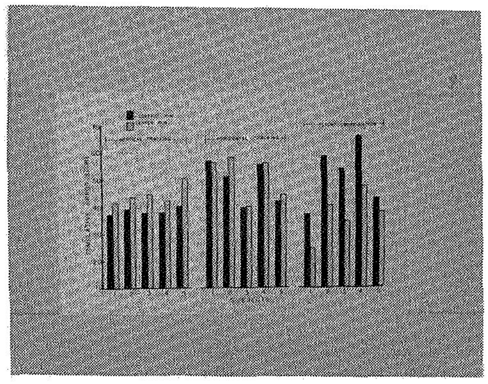

Figure 18:

Integrated error scores for performance of a tracking task during closed-loop centrifuge control and with the centrifuge stationary. Note the improvement in flight coordination and the degradation of vertical tracking during closed-loop control.

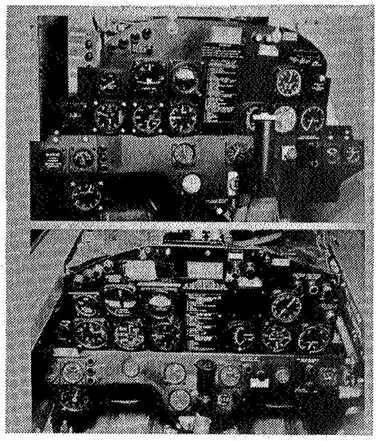

Figure 19: Instrument panel for a TV-2 aircraft simulation at the top and photograph of the actual panel at the bottom.

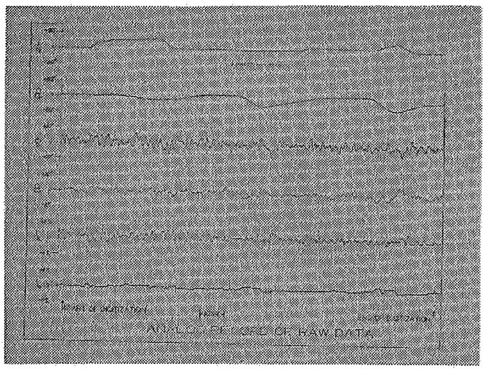

Figure 20: Analog record of raw data in a study of the validity of centrifuge simulations of the TV-2 aircraft.

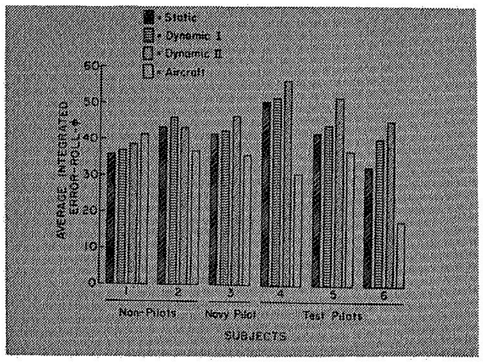

Figure 21: Integrated error scores for roll control in the TV-2 study.

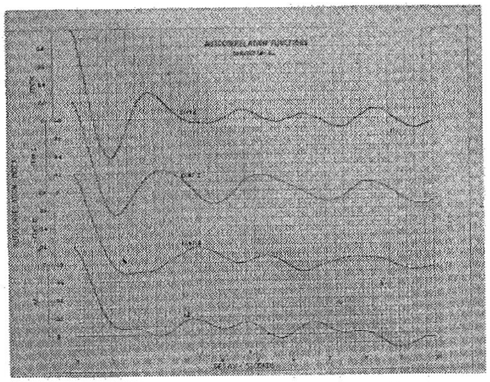

Figure 22: Autocorrelation index functions for roll control in the TV-2 study

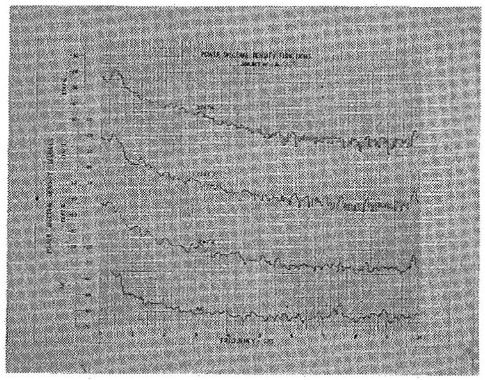

Figure 23: Power spectral density functions for roll control in the TV-2 study.

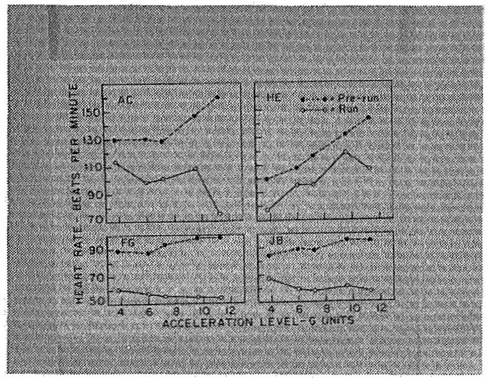

Figure 24: Subject heart rate as a function of acceleration. Dashed lines represent heart rate after the subject was told what acceleration would be, but before the run started. Solid lines represent heart rate during the run.